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Title:	AST Development in M2FCT (ASTWG and iDWG) Update to 21CTP
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AST Development in M2FCT (ASTWG and iDWG) Update to 21CTP

Rangachary (Mukund) Mukundan

January 20, 2020

Outline

- Introduction
  - AST Development
- ASTWG and International Collaborations
  - Membership/Timeline of ASTWG
  - Membership/Timeline iDWG
  - Resources – Path forward
- Progress in AST Development
  - Summary of results

Optional text box: use this for any details about the work

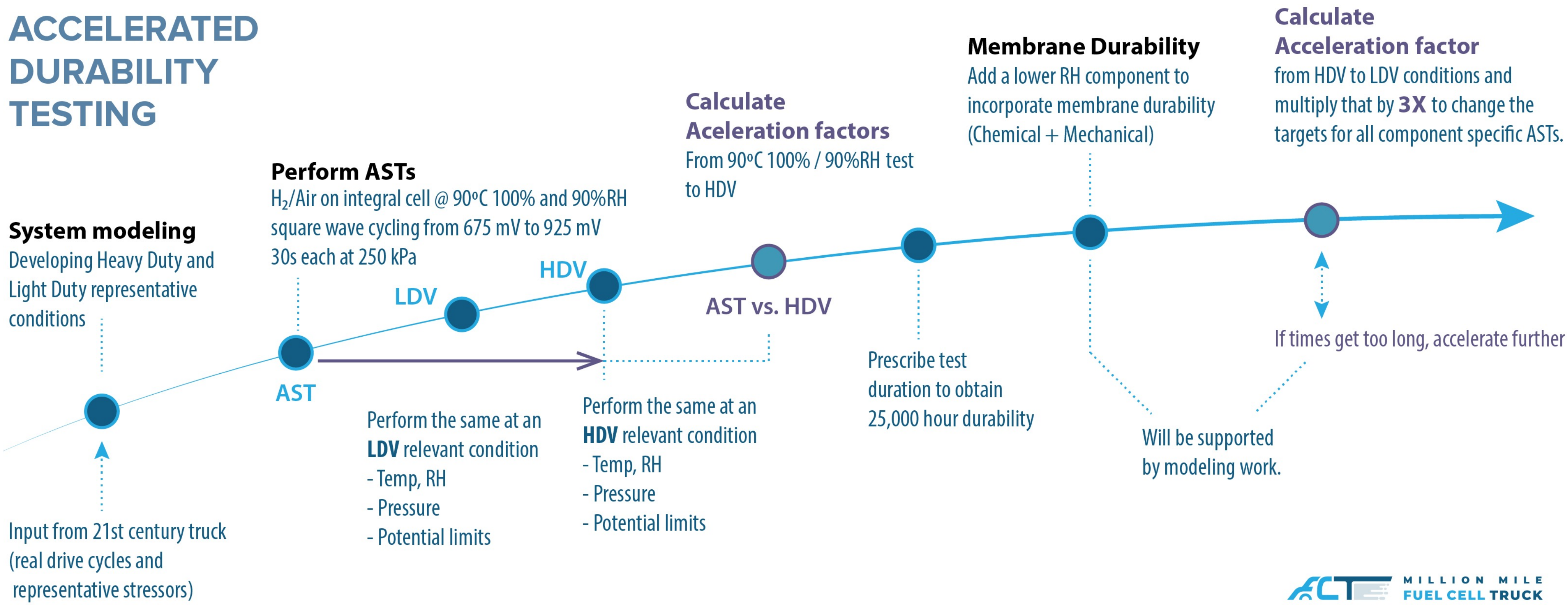
INTRODUCTION

Introduction

- Accelerated Stress Tests (ASTs) are required to evaluate fuel cell component durability in a reasonable time
- Current DOE and FCTT ASTs are light duty focused with 5000 – 8000 hour durability requirements
- Heavy duty ASTs need to reflect the 25000+ hour durability requirement
- Interim solution is to extend the duration of the current light duty ASTs
  - Catalyst AST has been extended from 30,000 cycles to 90,000 cycles (From 50 hours to 150 hours)
- Need to understand Heavy duty stressors and tailor ASTs for heavy duty applications
  - Longer lifetimes
  - Higher efficiencies – Higher loadings - Potentially higher operating temperatures and voltages
  - Heat rejection during low speed hill climbs – Higher operating temperature
  - Longer Idling times – Higher operating voltages and drier operation
  - Take into account different hybridization strategies (Vary size of battery)

Introduction

ACCELERATED DURABILITY TESTING



ASTWG and iDWG

ASTWG

- Recommend to the DOE: protocols and targets related to Heavy Duty Application of Fuel Cells

https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

3 Target Tables for Hydrogen Fueled Long-Haul Trucks

Table 1. Technical System Targets: Class 8 Long-Haul Tractor-Trailers (updated 10/31/19)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[9]
Fuel Cell System Lifetime[1,2]	hours	**25,000**	**30,000**
Fuel Cell System Cost[1,3,4]	\$/kW	**80**	**60**
Fuel Cell Efficiency (peak)	%	**68**	**72**
Hydrogen Fill Rate	kg H_2/min	**8**	**10**
Storage System Cycle Life[5]	cycles	**5,000**	**5,000**
Pressurized Storage System Cycle Life[6]	cycles	**11,000**	**11,000**
Hydrogen Storage System Cost[4,7,8]	\$/kWh (\$/kg H_2 stored)	**9 (300)**	**8 (266)**

M_2FCT 2025 Target
Achieve 2.5 kW/g_{PGM} power (1.07 A/cm^2 current density) at 0.7 V after 25,000 hour-equivalent accelerated durability test.[3]

ASTWG Membership / Timeline

- Membership : 29 members and 2 Affiliates
  - DOE, National Laboratories, Industry/University with DOE funded projects
    - GM, Nikola, Ballard, Plug Power, Cummins, Hyzon Motors, 3M, Chemours, W. L. Gore, CMU
    - Affiliates : Cell Centric and Hyundai
- Timeline
  - First meeting July 23rd, 2020 - 8th Meeting, October 28th, 2021
  - Ranked AST needs
  - Shared 21CTP data
  - Shared M2FCT system modeling and AST results with OEMs
  - OEM input on AST development received

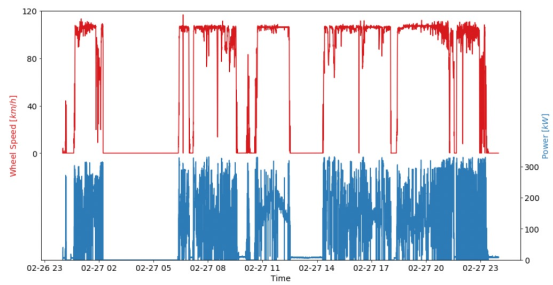
International Durability Working Group (iDWG)

- Co-ordinate work across continents and share strategies, protocols to promote fuel cells for heavy duty applications
- Led by M2FCT (USA), IMMORTAL (EU) and FC-PLATFORM (Japan)
- 85 Participants in addition to the ASTWG
- First meeting May 27th, 2021
  - Heavy Duty stressor
    - Methodology sharing between M2FCT, IMMORTAL and FC-PLATFORM
  - Characterization
    - Identification/development of advance characterization needs, Sample sharing
  - Baselining, MEA testing and Protocols
    - Potential to co-ordinate future protocols?

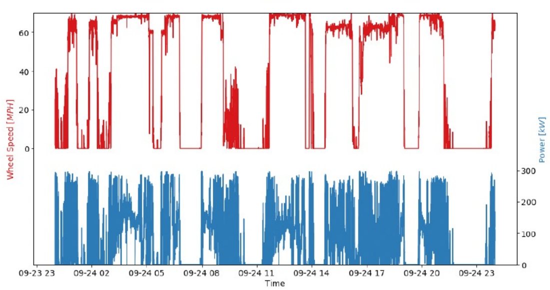
International Durability Working Group (iDWG)

21CTP : Jason Lustbader

Long-haul truck

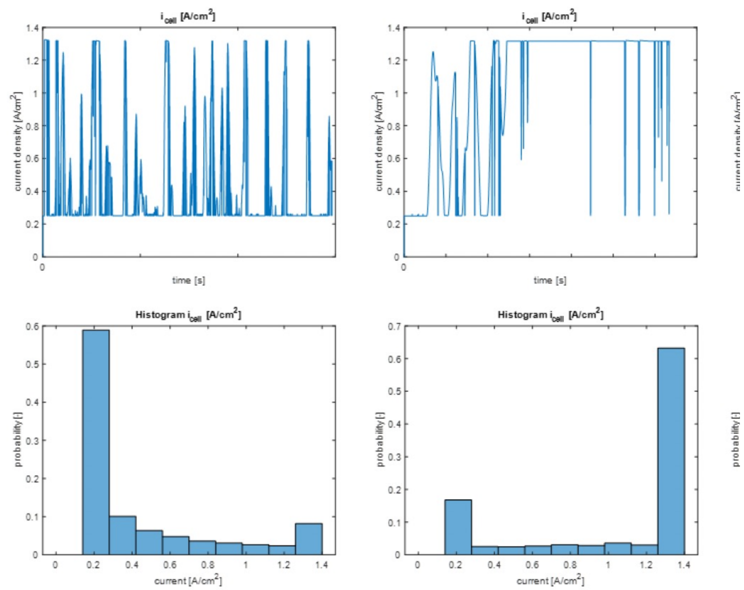


Max Engine Energy Consumption



IMMORTAL : Leonidas Tsikonis

(FC2, Mission1, 15°C, Controls1) (FC2, Mission2, 15°C, Controls1)



450 cases simulated (5 FCS designs, 6 Missions, 3 hybridizations, 5 ambient conditions)

TCRD labs : Takao Watanabe

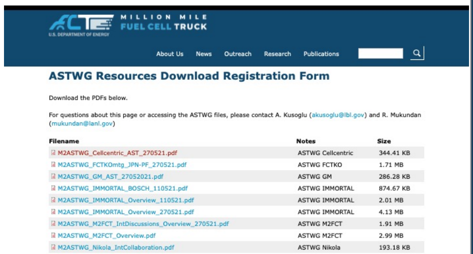
Shared Heavy duty. Specific simulated VIRs

Potentially targeting higher performance with increased loadings

Specific targets yet to be defined

- Drive cycles available, System modeling to convert to fuel cell operating conditions

Resources



MILLION MILE FUEL CELL TRUCK
U.S. DEPARTMENT OF ENERGY

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For questions about this page or accessing the ASTWG files, please contact A. Kusoglu (akusoglu@lbl.gov) and R. Mukundan (mukundan@lanl.gov)

Filename	Notes	Size
M2ASTWG_Cellcentric_AST_270521.pdf	ASTWG Cellcentric	344.41 KB
M2ASTWG_FCTKOmtg_JPN-PF_270521.pdf	ASTWG FCTKO	1.71 MB
M2ASTWG_GM_AST_27052021.pdf	ASTWG GM	286.28 KB
M2ASTWG_IMMORTAL_BOSCH_110521.pdf	ASTWG IMMORTAL	874.67 KB
M2ASTWG_IMMORTAL_Overview_110521.pdf	ASTWG IMMORTAL	2.01 MB
M2ASTWG_IMMORTAL_Overview_270521.pdf	ASTWG IMMORTAL	4.13 MB
M2ASTWG_M2FCT_IntDiscussions_Overview_270521.pdf	ASTWG M2FCT	1.91 MB
M2ASTWG_M2FCT_Overview.pdf	ASTWG M2FCT	2.99 MB
M2ASTWG_Nikola_IntCollaboration.pdf	ASTWG Nikola	193.18 KB

International Durability Working Group (iDWG)

8 Countries
from America, Europe, and Asia

30 Institutions
participants representing governments, universities, industry and labs

80 Researchers
facilitating data sharing, exchanging materials, promoting AST development

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IMMORTAL

NEDO New Energy and Industrial Technology Development Organization

FC-Platform

cea

Thermal Stressors
Chemical Stressors
Heavy-Duty Stressors
Mechanical Stressors
Chemical-Mechanical

Stressors related to Heavy Duty

Degradation Durability
Ex-situ Operando
Material Characterization
Multi-Modal
Multi-Scale

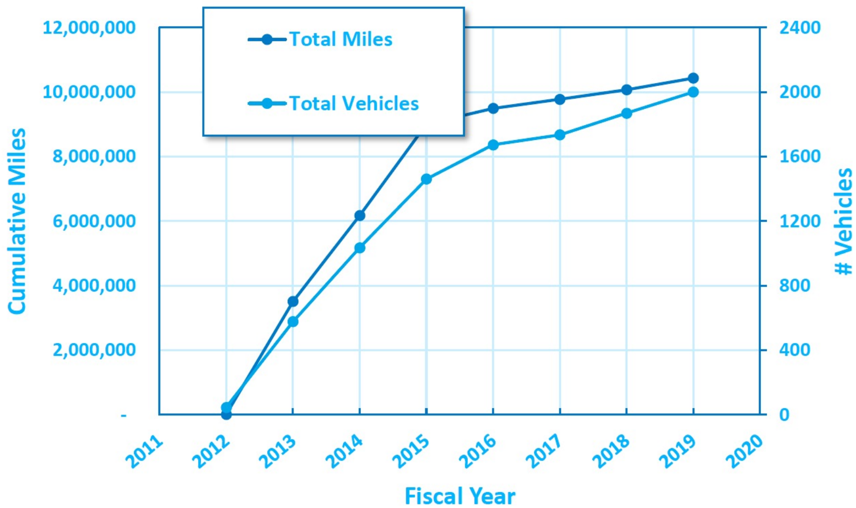
Characterization

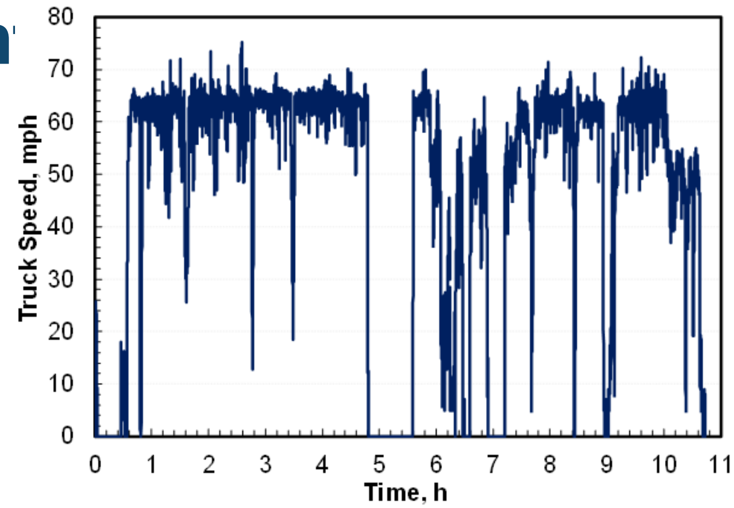
Benchmarking Baselining
Testing & Protocols
Benchmarking and Protocols
Durability Performance
Various Cell Sizes

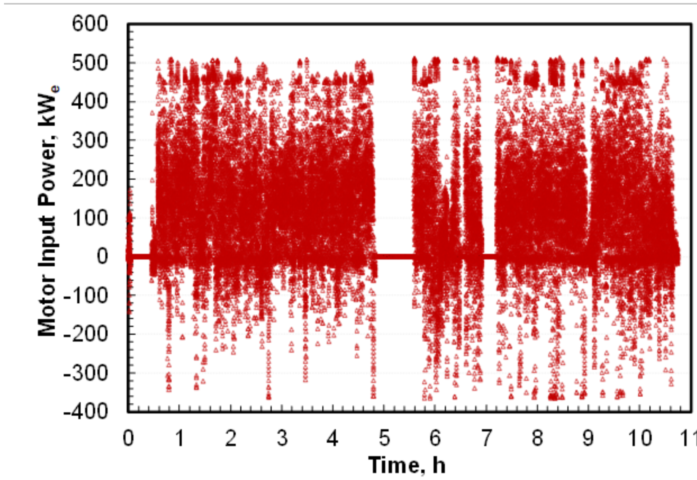
Benchmarking and Protocols

M2FCT AST Development

M2FCT – AST Developmen
Data obtained from 21CTP







Drive cycles obtained from NREL

Representative of maximum fuel consumption

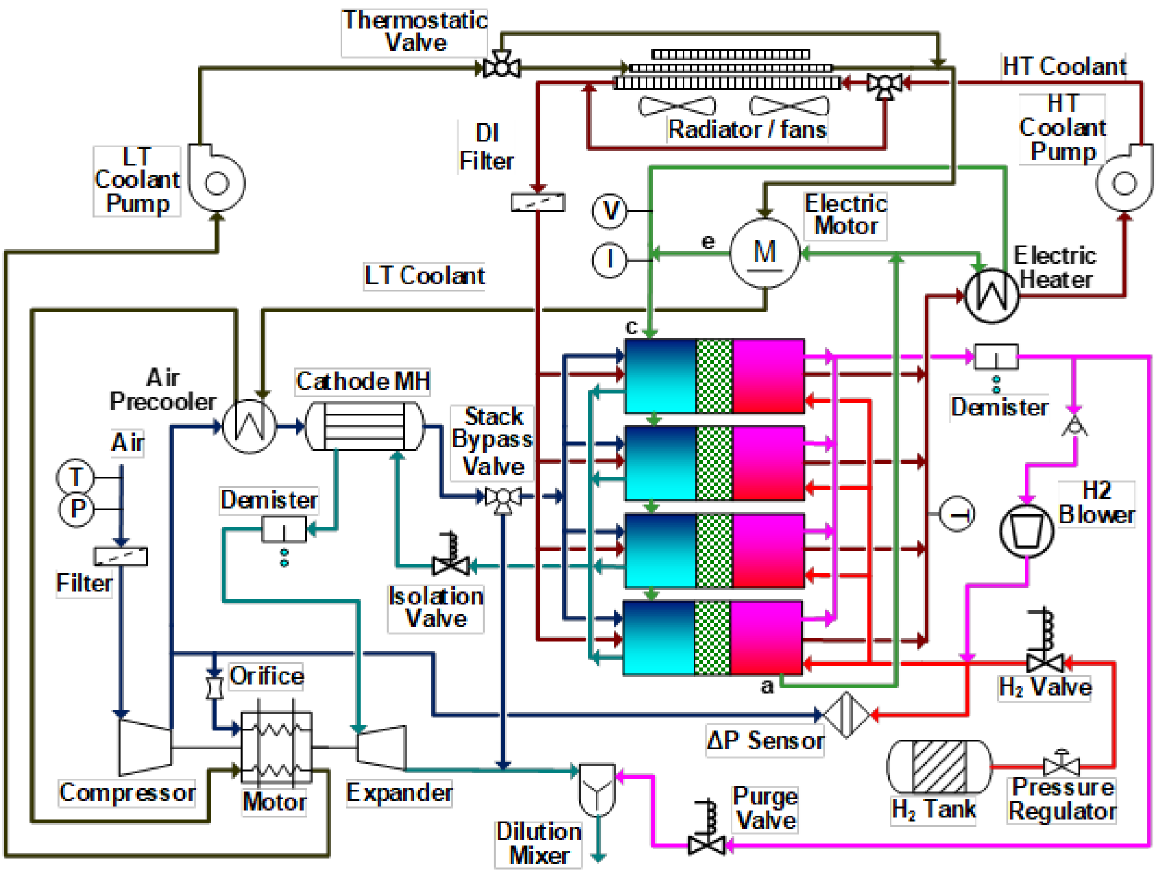
Working to obtain drive cycles representative of hill climb and maximum idle situations to better simulate durability

Drive-Cycle Rapid Investigation, Visualization, and Evaluation Tool (DRIVE)

Use GPS and CAN data to characterize vehicle operation and produce custom vehicle drive cycles based on real-world activity—analyzing thousands of hours of data in a matter of minutes.

Center for Integrated Mobility Science (CIMS): Commercial Vehicle Team Overview. Jason Lustbader (Team Lead)

M2FCT System Modeling



Salient Features

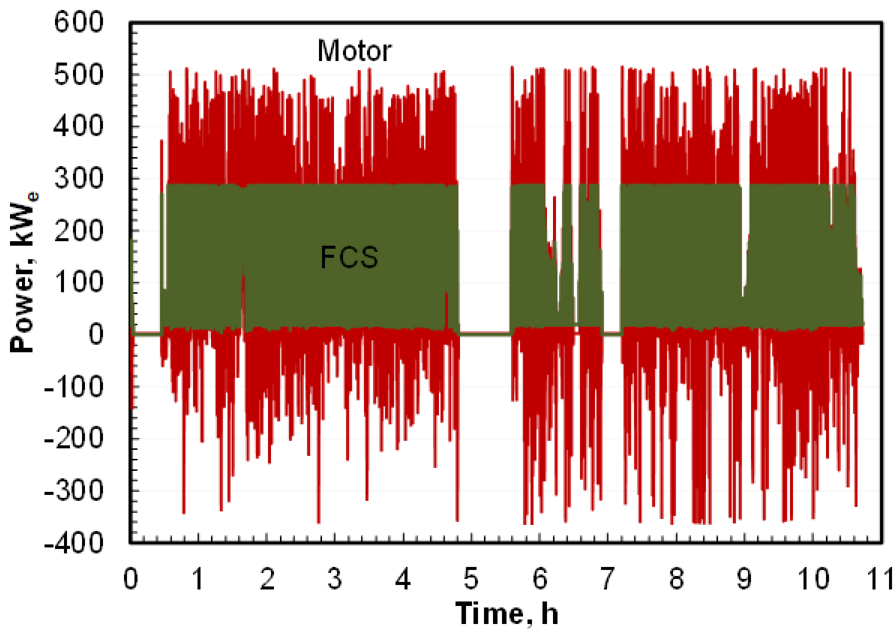
- 275 kW net (70-kWh ESS) at EOL
- Multiple stacks: 4
- Electrodes
  Cathode: a-Pt/C, 0.25 mg_{Pt}/cm^2, 50 wt.% Pt
  Anode: Pt/C w IrO_2 (TBD), 0.05 mg_{Pt}/cm2
- Membrane: 14 mm, chemically stabilized, mechanically reinforced
- Single air system with expander
- Single anode system with recirculation blower
- Cathode humidifier: No (TBD)
- Rated power conditions at EOL: 2.5 atm, 87-95ºC, 660-700 mV
- Control valves for startup and shutdown, cold start and OCV

M2FCT System Modeling

FCS Power

The battery is sufficiently large to prevent any unnecessary and damaging stack shut-down during all deceleration events on this duty cycle

- FCS idle power: 20 kW_e
- Total number of times FCS shut down during long-duration idle: 3



Energy Balance

FCS

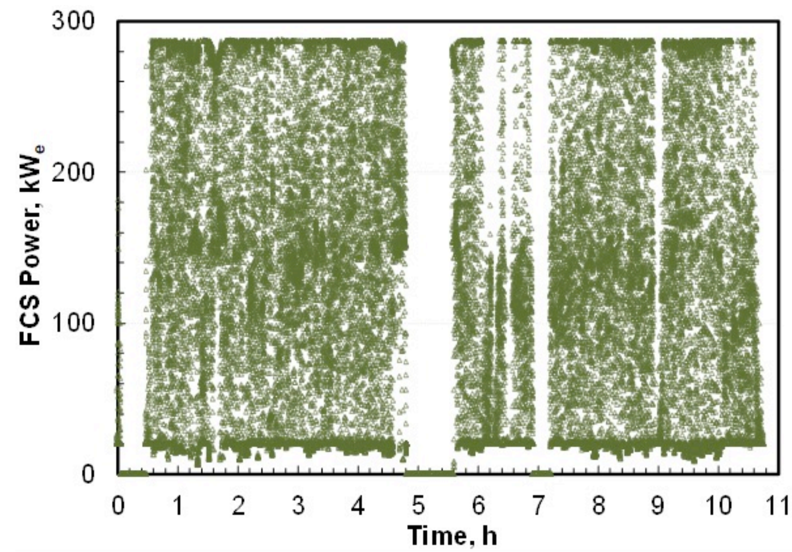
- Energy output: 1170 kWh

Motor

- Propulsion: 1212 kWh
- Regenerative energy captured: 107 kWh

ESS

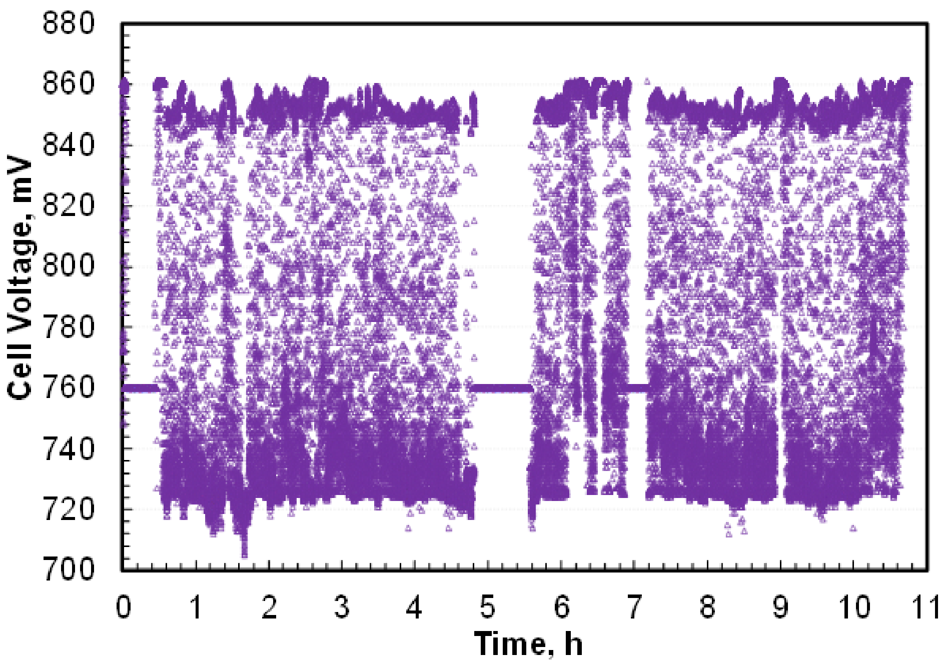
- Charging: 174 kWh
- Discharging: 142 kWh

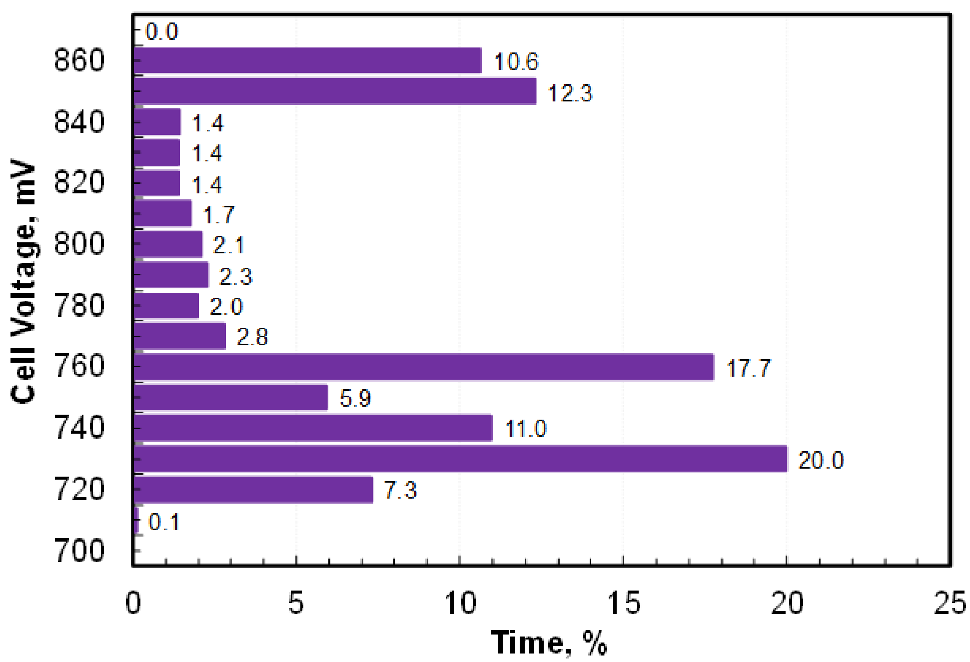


M2FCT System Modeling

Cell Voltage on Real World Drive Cycle
- 720 mV at 275-kW rated power
- 760 mV during stack shut down (needs experimental validation)
- 850 mV at 20-kW FCS idle power

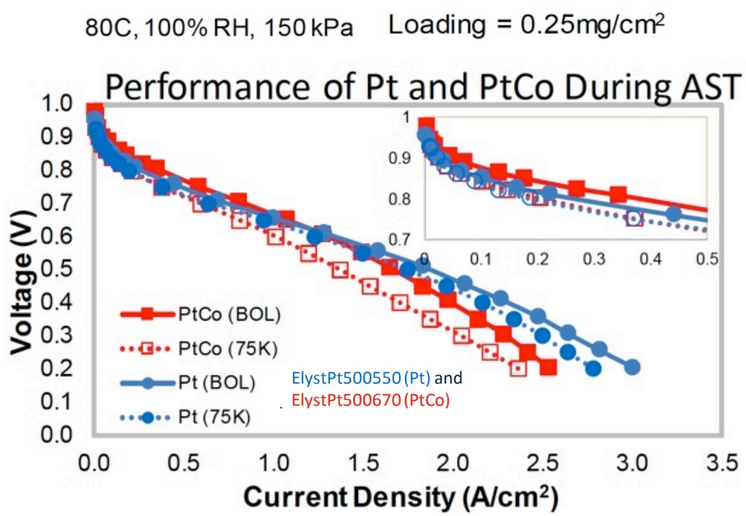
Cell Voltage Time Statistics
- 7.3% time at 720 mV (275-kW rated power)
- 17.7% time at 760 mV during stack shut down
- 22.9% time above 850 mV (20-kW FCS idle power)

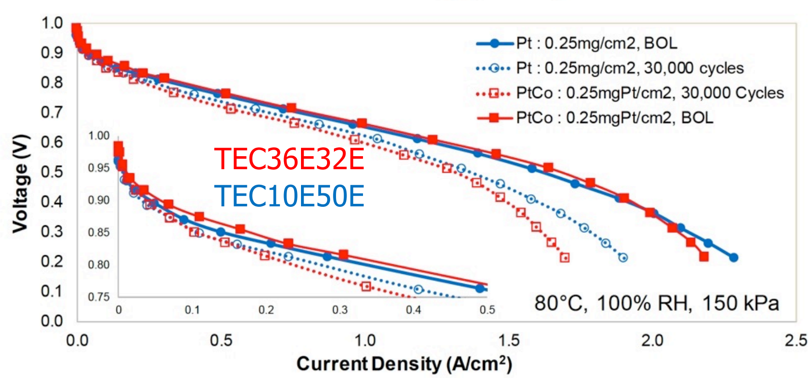


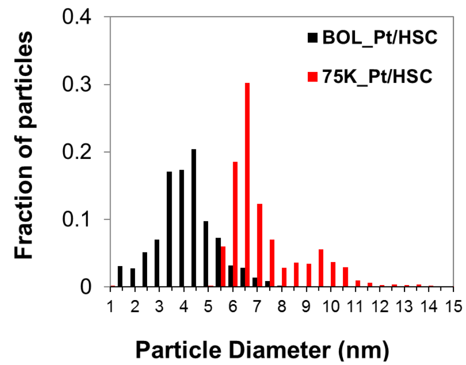


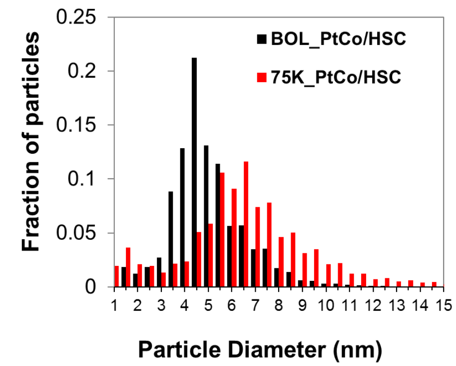
Catalyst AST

https://www.hydrogen.energy.gov/pdfs/review20/fc135_borup_weber_2020_o.pdf









Umicore Catalysts

	Mean diameter (nm)		
Sample	BOL	EOT	Δd (nm)
Pt/HSC 0.25mgPt/cm^2	4.3	7.5	3.2
PtCo/HSC 0.27mgPt/cm^2	5.2	6.8	1.6

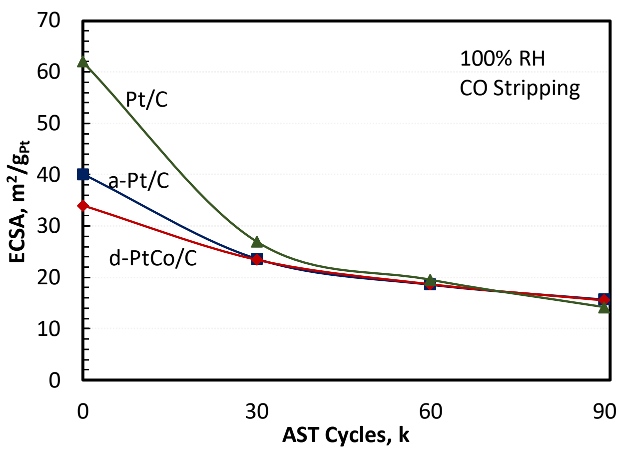
TEM shows 6.8 nm Pt and 6.4 nm PtCo particles after 75,000 cycles

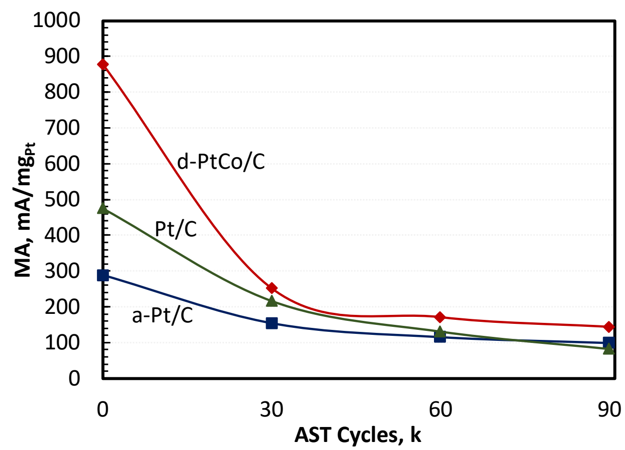
Baselining MEA Performance and Durability in Integral Cells

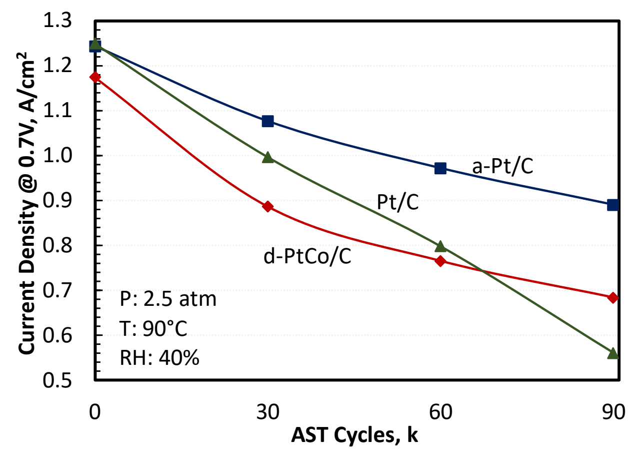
M^2FCT FY2021 Q4 Milestone

- **AST defined as 0.6 V – 0.95 V square wave with 0.5 s ramp and 2.5 s hold in H_2/N_2 at 80ºC and 100% RH, 90k cycles**
- **Integral Cell Conditions for Pol Curves: 1.5(c)/2(a), 2.5 atm, 90ºC, 40% RH**

	Number of Cycles	ECSA m^2/g_{Pt}	MA mA/mg_{Pt}	PD at 0.7 V mW/cm^2	PD at 0.7 V kW/g_{Pt}	PD at 1.07 A/cm^2 mW/cm^2	PD at 1.07 A/cm^2 kW/g_{Pt}
Pt/C	0k	62	476	874	2.9	772	2.5
	90k	14	82	393	1.3	647	2.1
a-Pt/C	0k	40	289	870	2.8	768	2.4
	90k	16	99	622	2.0	721	2.3
d-PtCo/C	0k	34	878	822	2.6	766	2.4
	90k	16	144	479	1.5	660	2.1



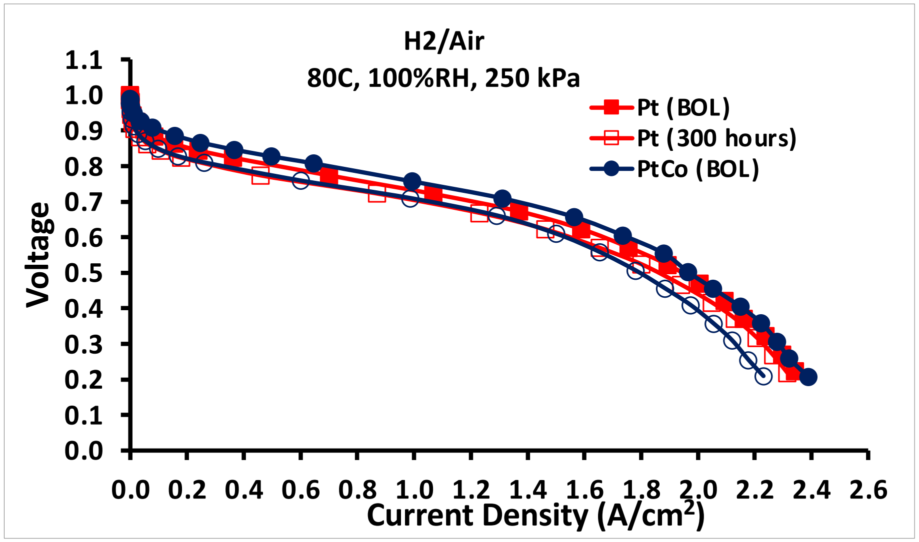


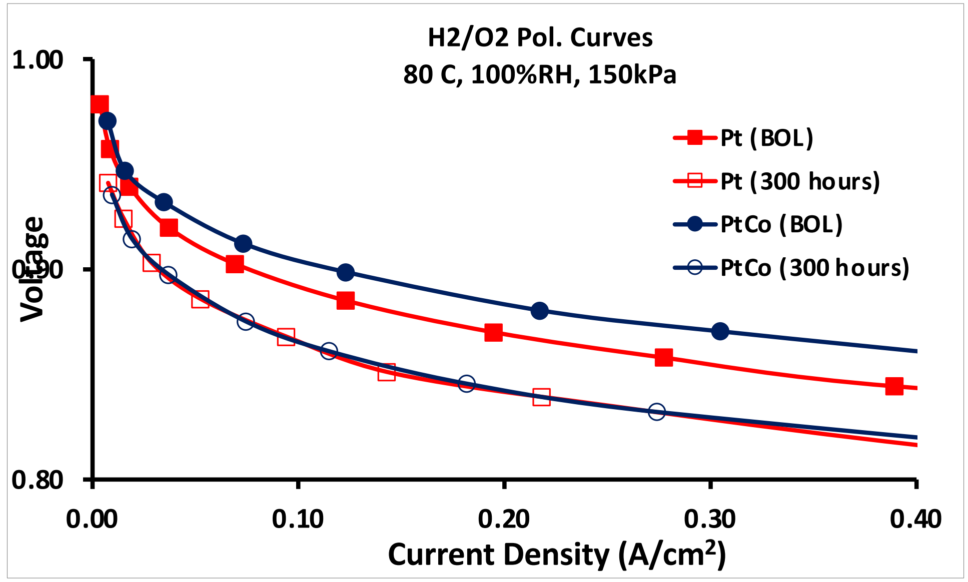


Current AST Development

- Perform ASTs in H_2/Air on integral cell @ 90 ºC, 100%RH with square wave cycling from 675 mV to 925 mV 30s each at 250 kPa
- Perform ASTs in H_2/Air on integral cell @ 90 ºC, 90%RH with square wave cycling from 675 mV to 925 mV 30s each at 250 kPa
- Perform the same at an HDV relevant condition (Temp, pressure, RH, potential limits)
- Calculate acceleration factors from 90 ºC, 100% RH, 90%RH/100%RH test to HDV conditions and prescribe test duration to obtain 25,000 hour durability
  - Timeline: FY 22
- Perform the same at an LDV relevant condition (Temp, pressure, RH, potential limits)
- Calculate acceleration factor from HDV to LDV conditions and multiply that by 3X to change the targets for all component specific ASTs. If times get too long, then we can further accelerate it. Will be supported by modeling work.
  - 2 years +
- Refine HDV cycle by including other stressors like high temp, high voltage, dry operation.

H_2/Air AST





Drop in performance correlated with Mass activity and ECSA loss

Co leaching and Pt particle size growth

Mass Activity	Hours	A/mg-Pt
	0	0.31
	50	0.23
	100	0.21
	200	0.17
	300	0.13

Mass Activity	Hours	A/mg-Pt
	0	0.47
	50	0.33
	100	0.23
	200	0.18
	300	0.14

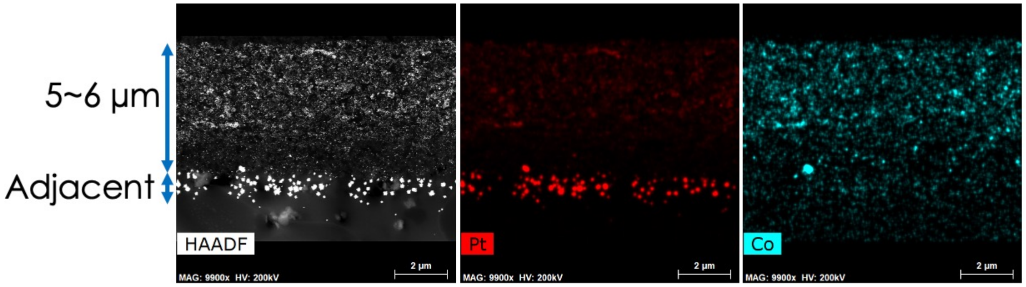
Compare H_2/Air and H_2/N_2 ASTs

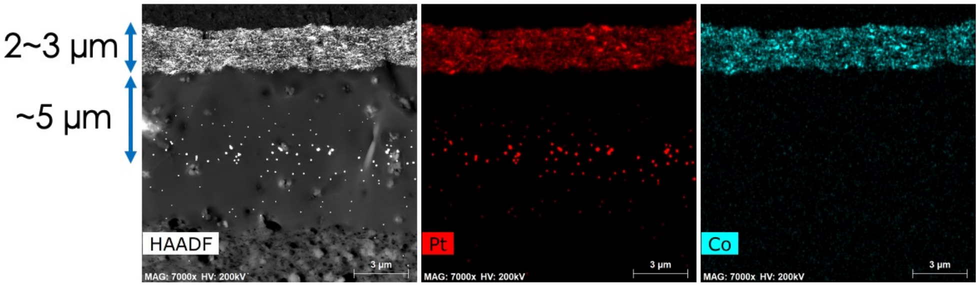
AST in N2, 80 ºC, 0.6V to 0.95V, 90k cycles

	Co at.%	Pt loss%
Map1	13.0	36.7
Map2	12.6	34.2
Map3	13.9	37.9
Average	13.2±0.5	36.3±1.5

AST in Air 300 hrs. 90 ºC, 90%RH, 0.675 to 0.925V

	Co at.%	Pt loss%*
Map1	21.3	12.1
Map2	21.8	15.8
Map3	21.6	10.7
Average	21.6±0.2	12.9±2.2



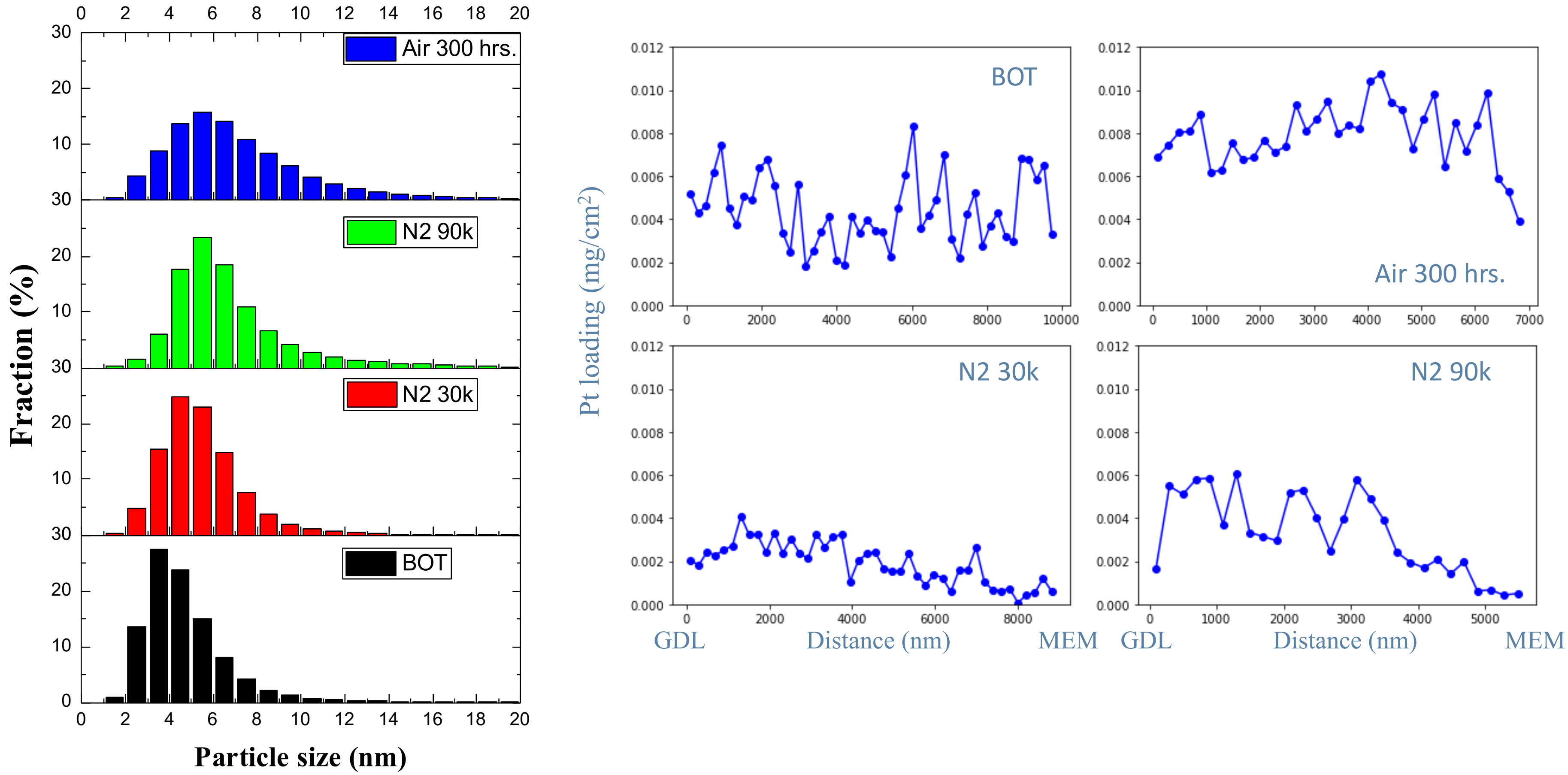


Compare H_2/Air and H_2/N_2 ASTs

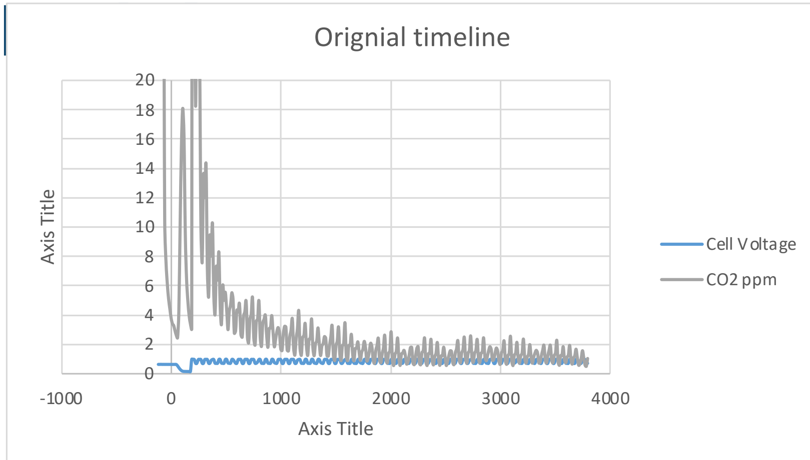
Compare high throughput analysis:
Overall particle size

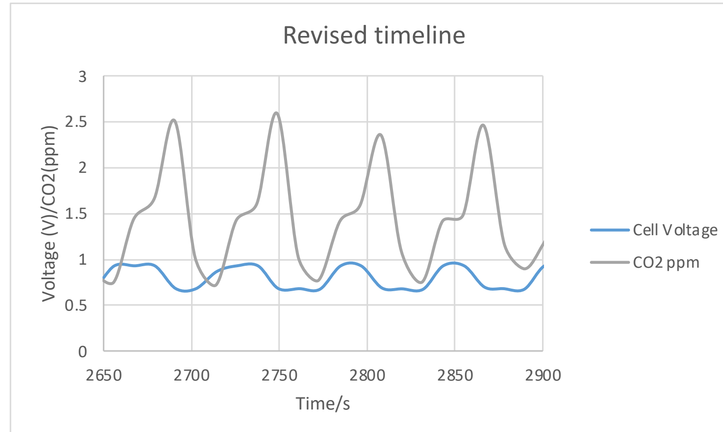
	1112 N_2 BOL	1112 N_2 30k	1112 N_2 90k	K22 Air 300 hrs.
Analyzed area (μm^2)				
Total number of particles analyzed	123515	72764	22964	98704
Median (nm)	4.3	5.2	6.0	6.5
25%-75% (nm)	3.4-5.5	4.2-6.4	4.9-7.6	4.8-8.8
Median (<10 nm)	4.2	5.1	5.8	5.9
25%-75% (<10 nm)	3.4-5.4	4.2-6.2	4.8-7.0	4.5-7.4
Median (≥10 nm)	13.3	11.8	12.3	12.6
25%-75% (≥10 nm)	11.2-18.2	10.7-14.1	11.0-15.0	11.0-16.0
Electrode thickness (µm)	9.6	8.8	5.5	6.8
Estimated Pt loading (mg/cm2)				

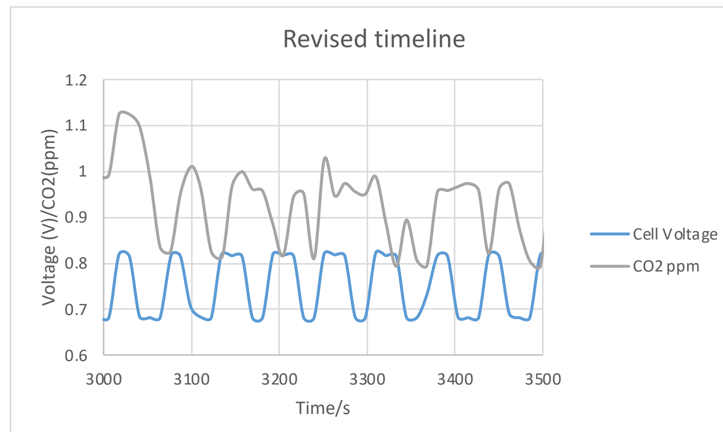
Compare H_2/Air and H_2/N_2 ASTs



Carbon corrosion and Fluoride emission during







- Carbon corrosion and electrode thinning observed
- Dramatically decreases with time
- FER ≈ 0.5 $\mu g/cm^2/hr$ for Nafion HP and > 2 $\mu g/cm^2/hr$ for N211

CONCLUSIONS

- ASTWG
  - DOE, National Labs, Companies and Universities with DOE projects
  - Recommend Heavy duty specific ASTs for PEMFCs
- iDWG
  - Co-ordinated by M2FCT, IMMORTAL and FC-PLATFORM
  - Over 85 researchers from around the world sharing information
- AST Development
  - H_2/N_2 catalyst AST to 90,000 cycles (0.6V to 0.95V)
  - H_2/Air AST at 90 ºC, 0.675V to 0.925V
  - Heavy duty drive cycle data from 21CTP being utilized in fuel cell system models to develop heavy duty specific fuel cell testing conditions
  - NDIR and Fluoride emission used to quantify carbon corrosion and membrane degradation during AST

Acknowledgements

- Truck Drive cycle data – Jason Lustbader (NREL)
- System modeling – Rajesh Ahluwalia and Joshua Wang (ANL)
- H2/N2 ASTs – K. C. Neyerlin and Leiming Hu (NREL)
- H2/Air ASTs – Xiojing Wang, Siddharth Komini Babu, Tanya Agarwal, Rodney Borup and Rangachary Mukundan (LANL)
- TEM – Dave Cullen and Haoran Yu (ORNL)
- XRD – Debbie Myers and Nancy Kariuki (ANL)
- Membrane characterization - Ahmet Kusoglu and Adam Weber (LBNL)
- iDWG and AST websites - Ahmet Kusoglu (LBNL)